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INVESTIGATION OF THE COMPONENTS OF THE NAL HIGH REYNOLDS  
NUMBER TWO-DIMENSIONAL WIND TUNNEL, Part IV  
DESIGN, CONSTRUCTION AND PERFORMANCE OF THE EXHAUST SILENCER

By

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(NASA-TM-88513) INVESTIGATION OF THE  
COMPONENTS OF THE NAL HIGH REYNOLDS NUMBER  
TWO-DIMENSIONAL WIND TUNNEL. PART 4: DESIGN,  
CONSTRUCTION AND PERFORMANCE OF THE EXHAUST  
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## 1. INTRODUCTION

This research center has been conducting the preparation of a 1 M x 0.3 M two-dimensional wind tunnel (8)(13) shown in Fig. 1 and 2 in order to promote the research and development of a new wing design which will provide transport airplanes with more economical lift. The project has been completed with the exception of some support devices. (9) For the purpose of avoiding the problems caused by discrepancies in the Reynolds number (3)(4) which are associated with the construction of oversized and high speed transport airplanes, said wind tunnel is designed to be operated under much higher pressure level (approximately 10 times as high as the pressure level of the existing wind tunnels). Because the wind tunnel is built according to the intermittent blow down design in order to save the construction cost, the maximum of 833 Kg/sec of pressurized air must be discharged into the atmosphere. It goes without saying that extremely high level of noise is generated at this time. Therefore, strict adherence to the municipal anti-noise pollution ordinance was expected since this research center is located adjacent to a class II residential zone (18). This is why matters concerning aerodynamic element as well as noise pollution have been carefully studied since the beginning of this project. Large volume of pressurized air that is discharged at the time of

the operation of the wind tunnel is first decompressed by three porous panels (17) installed at the down stream of the wind tunnel and converted into a noise consisting predominantly of high frequency element so that reduction of the noise level will be accomplished easier. Since the sound energy discharged from the very end of the wind tunnel, a discharge pipe, is estimated to reach 163 dB, it was determined that a considerable work had to be done before the noise level was brought down to the permissible level of 45 dB (A).

The construction of the sound suppressor device (Fig. 3) was accomplished considering the following items.

(1) Splitter type sound suppressor should be used so as to avoid the construction of an oversized device.

(2) Noise absorption surface (eg., each sound suppressor and walls of the wind tunnel) which makes the direct contact with the air flow provides high level of noise absorption of various ranges including the low frequency range. Therefore, thickness of the noise absorption material is determined at 100 mm - 150 mm. In addition to that, it should be supplemented by as much background air layer as possible.

(3) As the noise absorption material, glass wool boards made of glass wool which showed rapid development in recent years are used. These boards must be intact after the

completion of the device.

(4) Connection of various parts must be accomplished through welding not through the use of screws and the like.

(5) The height of the structure should be restricted to 20 meters in order to save the construction and related cost.

(6) The level of the low range noise that can be easily lost through the walls should be reduced at the upper stream as much as possible.

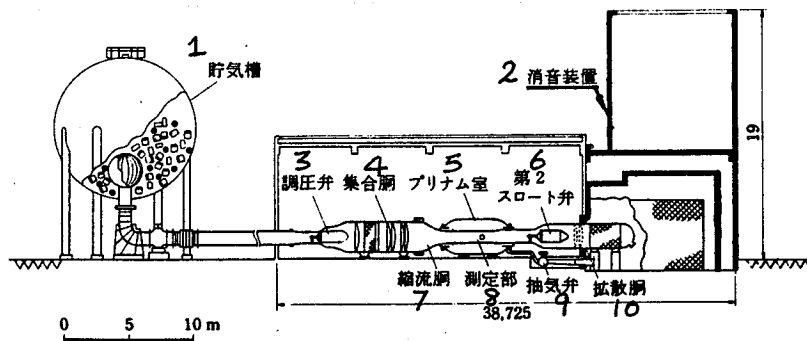
(7) In order to reduce the level of the noise loss through the walls, the upper stream side should be equipped with a double wall.

(8) Noise reduction of the high mach wind tunnel (12) ( $M = 5,15 \text{ CM} \times 15 \text{ CM}$ ) and the air intake valve for air compressor ( $19,150 \text{ NM}^3/\text{hour}$ ) is accomplished by this device.

(9) (omitted)

(10) The upper stream area where the flow passage is narrow must have the air pressure low in order to reduce the self-generated noise.

Fig. 1 The entire view of the two-dimensional wind tunnel



1. air storage tank    2. sound suppressor device    3.  
pressure control valve    4. consolidation tunnel    5. prnamu  
\* chamber    6. 2nd throat valve    7. air flow condensation  
tunnel    8. measurement part    9. air injection valve    10.  
diffusion tunnel

Fig. 2 The total view of the two-dimensional wind tunnel

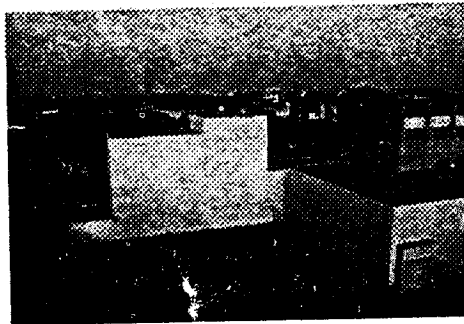


図2 二次元風洞全景

Considering the above listed items, sound suppressors which are believed to be effective in handling the low range noise and variable form splitter type sound suppressors consisting of three kinds and six steps from the wider ones to narrower ones were installed. At the down stream, a 180 degrees bent duct as well as a 90 degrees bent duct were arranged in order to handle the high range noise. Test of

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this device indicated that noise reduction at the maximum of 82 dB (500 Hz) and the minimum of 42 dB (63 Hz) had been accomplished by the variable form splitter type sound suppressor alone. This device as a whole has been characterized to possess the capability to accomplish the noise reduction according to the design although it was rather difficult to distinguish between the noise of the two-dimensional wind tunnel during its operation and the high level of (other) hidden noises.

This essay attempts to describe the design and construction process of the two-dimensional wind tunnel as accurately as possible. It is the view of the authors that the anti-noise pollution laws and regulations will become more and more severe each year making the demand for the noise reduction devices greater. The fact of the matter is that the availability of resources concerning large scale noise reduction devices are extremely poor. A half of this essay attempts to reveal the characteristics of the noise generated by the two-dimensional wind tunnel. The other half of this essay describes the design, structure and characteristics tests.

Fig. 3 The entire view of the two-dimensional sound suppressor

Fig. 3

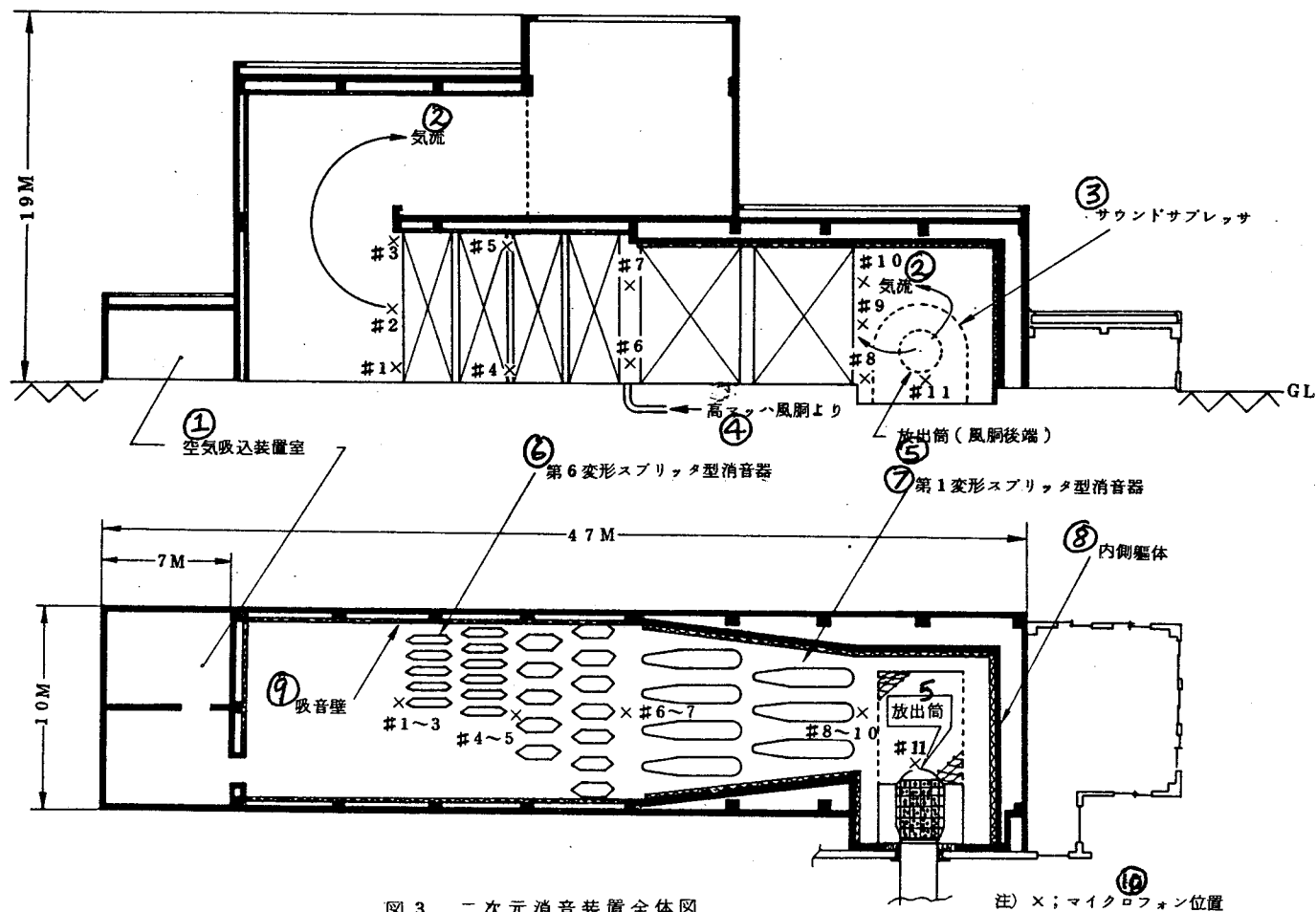


図3 二次元消音装置全体図

1. air inlet device chamber    2. air flow    3. sound  
suppressor    4. from high mach wind tunnel    5. discharge tube  
6. sixth variable form splitter type sound suppressor    7.  
first variable form splitter type sound suppressor    8. inner  
housing    9. noise absorbing wall    10. position of a  
microphone

## 2.. MARKS

M ; mach number                      Po ; stagnant pressure  
PWL; sound power level              S h; straw hull \* number  
C ; speed of sound  
D ; valve throat width, splitter width or duct width  
G ; weight and flow volume of air  
fp ; center frequency  
a ; length of short side of a square exit  
b ; length of long side of a square exit  
r ; sound source and sound reception point distance  
Ad ; distance subtrahend     $\pi$  ; pi  
SPL; sound pressure level  
S ; cross sectional square measurement of flow passage  
 $\zeta$  ; resistance coefficient    u ; flow speed  
f ; frequency  
M ; surface density (M1, M2 in case of a double wall)  
TL<sub>o</sub>; transmission loss against vertically received sound



wave

TL ; transmission loss (TL1, TL2 in case of a double wall)

Cb ; speed of the bent wave on the surface of a plate

t ; thickness                      fc ; coincidence frequency

fr ; low sound resonance frequency

$\rho C^2/d$ ; spring coefficient of a double wall air layer

d ; distance between two (double) walls

$\rho$  ; air density                       $\gamma$  ; density of glass wool

board

PT ; air tank pressure               $\phi$  ; diameter

P3 ; rear area pressure of the second throat valve

P4 ; rear area pressure of the first porous  
board of a diffusion tube

P5 ; rear area pressure of the second porous  
board of a diffusion tube

### 3. ESTIMATE OF THE TOTAL SOUND OUTPUT

#### 3.1 Air flow within the wind tunnel

The air that is compressed to 20 Kg/ square cm G by an air compressor is stored in an air storage tank for a while. It is then led to the pressure regulation valve located at the far upstream of the wind tunnel through a high pressure tube (1 M to 0.8 M in diameter). The function of the

pressure regulation valve is to maintain the air pressure within the consolidation tunnel at a predetermined level (2 - 12 Kg/ CM<sup>2</sup> abs). The air flow after passing through the regulation valve is jet-sprayed into the consolidation tunnel as a jet of air containing impact wave while the pressure level within the air tank is much higher than that within the consolidation tunnel. Within the consolidation tunnel are a porous board and a various splitter type sound suppressor (length, 1 M x width, 10 CM; width of the flow passage, 10 CM) which conduct commutation and noise reduction. Toward the down stream direction of the porous board and the splitter type muffle are four sheets of steel mesh for commutation. (8) Although noises may also be generated from each one of these parts, the flow speed at the consolidation tunnel does not exceed 12 M/ sec, and it can be ignored. The air flow which passed the consolidation tunnel enters the air flow condensation tunnel. At the upper and lower parts of the wall of the measurement part is a channel shaped opening (maximum opening area ratio: 10 %), through which a part of the air flow is discharged into the sound suppressor the air injection valve. In addition to that, a method of operation in which a small volume of air is sucked in from the right and the left side walls of the measurement part is also carried out occasionally. Yet, flow volume of the above operation is so small (only a few % of the total flow volume) that its

influence can almost be ignored. The flow which passed through the measurement part is again compressed at the second throat valve part changing itself into the same kind of flow as that at the pressure control valve and enters the diffusion tunnel. There are two pieces of porous boards placed inside the diffusion tunnel. By the resistance of these two porous boards, the air flow loses its aerodynamic characteristics and enters the discharge tunnel. The outer circumference of the discharge tunnel is made of porous board through which the air flow is jet-sprayed out. The discharge tunnel is set up inside a sound suppressor (Fig. 7) which is believed to have noise reduction effect of low frequency sound. The air flow is jet-sprayed out of numerous holes drilled through the circumference of the sound suppressor.

It is believed that the air flow within the wind tunnel behaves the way described above. It is a well known fact that the higher the flow speed is, the higher the noise level is. The same goes if the pressure ratio of the front and the back far exceeds the sound of speed. (1) Accordingly, it is estimated that the majority of the noises generated at the two-dimensional wind tunnel is generated at the pressure control valve part, the second throat valve and the diffusion tunnel.

### 3.2 Self-generated noise of the pressure control valve

In case the pressure ratio between the points before

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and after entering the valve exceeds 2 as seen in the case of the pressure control valve or the second throat valve, increase in impact wave noise becomes more significant compared to the increase in the noise level by the mixture of turbulence. Particularly, if the above described ratio exceeds 3, the majority of the noises is caused by the impact wave. It is believed that the noise by the mixture of turbulent flow can be ignored in this situation. (1)

In the case of the pressure control valve, the pressure ratio between the points before and after entering the valve is determined almost exclusively by the pressure level of the air storage tank and the consolidation tunnel. Therefore, the sound power level is determined by the pressure level and flow level of the above. While the pressure level of the air storage tank is lowered as the operation time (in seconds) of the wind tunnel passes, the pressure level of the consolidation tunnel remains the same at the predetermined level. Therefore, the pressure ratio before and after entering the valve hits the peak at the moment when the wind tunnel is started. As for the flow ratio, it increases in proportion to the  $P_o$  if the predetermined mach number is identical. In case  $P_o$  is the same, it increases according to the increase in the predetermined mach number. And when  $M = 1$  is exceeded, the flow volume is determined solely by  $P_o$ . Therefore, only the case of  $M = 1$  should be considered in the

determination of the maximum flow volume of each  $P_0$ . If the pressure ratio before and after the control valve as well as the flow volume are high, the sound power energy should become the maximum. Yet, the pressure ratio before and after the valve becomes higher as the predetermined  $P_0$  becomes lower. On the contrary, this will cause the reduction in the sound power energy because this will reduce the flow volume. Fig. 4 makes the estimated calculation of this situation. The maximum figure of the self-generated sound of the pressure control valve is in the vicinity of 1/2 of the maximum flow volume. It becomes the maximum at  $P_0 = 7$  ata, and its figure is 159 dB (10 watts standard).

Fig. 4 Relationship between sound power level generated by the pressure control valve and  $P_0$

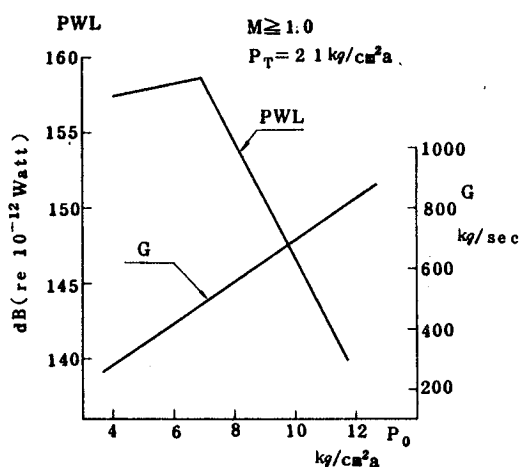


図4 調圧弁が発する音響パワーレベルと  $P_0$  の関係

Next, let us consider the frequency characteristics of the noise generated by the pressure control valve. Distribution of the power spectrum density of the noise generated by the valve is generally believed to be wide and therefore difficult to determine the maximum frequency distribution. However, it is believed that there is quite difference in the distribution between the the one by the mixture of turbulent flow and by the impact wave. In the case of sub-sonic speed using the straw hull number  $Sh$  as the zero-dimension frequency, the maximum figure of the spectrum density appears between  $Sh = 0.1 - 0.2$ . Measurement which is approximately 20 dB toward the lower frequency range from the above and approximately 40 dB toward the higher frequency range is considered the average spectrum density distribution. In the impact wave noise whose pressure ratio is much higher than the above, the maximum figure of the spectrum density appears between  $Sh = 0.05 - 0.65$  according to the changes made to the pressure ratio between before and after passing through the valve. At the frequency range lower than the above, reduction of approximately 30 dB per a decade is shown; at the frequency range higher than the above, reduction of approximately 25 dB per a decade is revealed. (This is nearly a symmetric spectrum density distribution.) (1)

$$Sh = fpD / C \dots\dots\dots(1)$$

Therefore, the central frequency at the time of the

maximum sound power of the pressure control valve can be shown as follows considering the degree of the opening of the valve since the before/ after pressure ratio is about 3:  $f_P \approx 900$  Hz. This is a figure of the noise level that is relatively easy to suppress. The central frequency in the case of the pressure control valve changes according to the time (seconds) elapsed from the beginning of the operation of the wind tunnel as well as the degree of the valve opening. Yet, since the way the pressure ratio and the degree of the valve opening influence the central frequency is reciprocally inverse, these two tend to cancel each other, and the central frequency will not change much. It has been reported (2) that the measurement figure of a valve of the other wind tunnels which is shaped identical to the pressure control valve has nearly flat characteristics. Incidentally, the similar measurement figure has been obtained in the case of the second throat valve of this wind tunnel to be mentioned later.

### 3.3 Self-generated sound of the second throat valve

Because the sound generated at the second throat valve is caused by the flow whose total pressure is kept at a certain level by the pressure control valve, it is believed that such sound will not change according to the elapsed time (seconds) after the starting of the wind tunnel as seen in the case of the pressure control valve part.

Fig. 5 shows the pressure and flow volume

relationship between the second throat valve and the porous board part for decompression that is established toward the down stream direction of the second throat. The pressure level at the down stream of the second throat valve is determined by the level of resistance (17) that is provided according to the flow volume. As mentioned at 3.2, in case the pressure ratio before and after the valve exceeds 2, the level of the self-generated sound is controlled primarily by the pressure ratio, not by the flow volume. (1) It is believed that the maximum figure is obtained at the pressure ratio of 3. In the case of the second throat, it is not at the time of the maximum flow when the above pressure ratio is reached. It is when the valve is closed a little. In other words, the pressure level at the down stream of the valve will go up as the pressure level is increased, while the maximum pressure at the upper stream is 12 ata. It is in the vicinity of  $G = 550 \text{ Kg/ sec}$  when the pressure ratio before and after the valve exceeds 3. At this time, it is believed that the sound power level generated by the second throat valve reaches 163 dB. It is obvious that this figure is far higher than the self-generated sound level of the pressure control valve. At this time, the self-generated sound by the porous board is approximately 154 dB (the figure of the first porous board which has the highest before/ after pressure ratio). As clearly shown in Fig. 5, the before/ after pressure ratio of



the first porous board remains almost the same between  $G = 600$  Kg/ sec and  $G = 833$  Kg/ sec. Therefore, the self-generated sound of the porous board is generated at the time of the maximum flow volume, and its level is believed to be approximately 155 dB.

Next, the sound power density distribution is described. Impact noise is provided by the width of the valve closure as well as the before/ after pressure ratio as described earlier. However, it has been reported that the actually measured figure is flat. Since the performance test to be described later also indicates the same result, it may be proper to think that the design possesses flat frequency characteristics.

Fig. 5 Pressure change inside the diffusion tube by flow volume

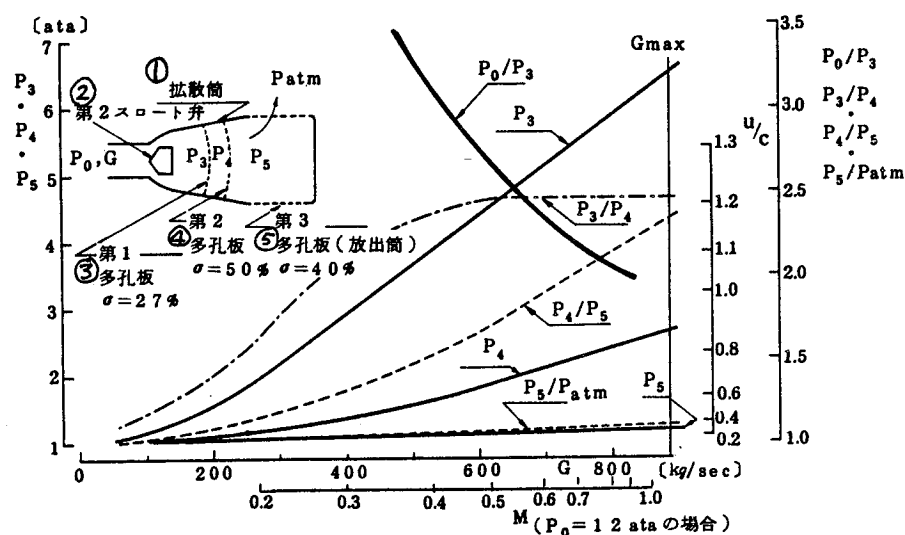


図5 流量による拡散筒内部の圧力変化

1. diffusion tube    2. second throat valve    3. first porous board  
4. second porous board    5. third porous board

### 3.4 Characteristics of the sound generated by the wind tunnel

From the above estimate, the sound power level generated by the two-dimensional wind tunnel is assumed to be 163 dB ( $10^{-12}$  watts standard) possessing a flat sound power spectrum density distribution. Design of a sound suppression device (sound suppressor) which is capable of reducing the noise level to below 45 dB at the boundary of the research center is considered next.

## 4. CONCEPTIONAL DESIGN OF THE SOUND SUPPRESSION DEVICE

In the case of the sound suppression device being considered here, distance of 100 meters separates at the nearest two points between the outlet of the sound suppression device and the boundary of the research center which is most likely to experience the problem of the noise pollution. Between these two points, the noise will be affected by distance and absorption by air. In addition to that, the noise will also be absorbed by buildings and ground. Weakening of the noise by the temperature difference is also

considered.

#### 4.1 Weakening (of the noise level) by distance

Since the outlet of the sound suppression device can be considered as a sort of surface sound source, weakening of the noise level by distance can be shown in the following formula:

$$Ad = 10 \log b / a + 20 \log r / b \dots\dots(2)$$

As the outlet of the sound suppression device is set at 8.5 to 9 M, weakening of the noise level by approximately 31 dB can be expected at the distance of 100 M.

#### 4.2 Sound absorption structure and its size

[Determination of the flow passage cross-sectional square measurement] The permissible sound pressure at the outlet of the sound suppression device has been determined to be below 69 dB ( $4 \times 10^{-4}$   $\mu$  bar standard) in the case of the white color noise considering the weakening process relative to the distance alone. The sound power energy of the air being discharged from the outlet at this time is believed to be 89 dB from the formula (4).

$$PWL = SPL + 10 \log S \dots\dots(4)$$

Since this device consists of the splitter type sound suppressor and the bent duct type sound suppressor, the self-generated sound that is generated when the passage is too narrow is believed to be caused by these parts. On the contrary, if the square measurement of the flow passage is too

wide, then the sound suppressor becomes too big in size costing too much to build.

Since the splitter type sound suppressor is thought to have the highest level of the self-generated noise, it is recommended that a streamline shaped device should be used as much as possible. Considering the fact that the resistance coefficient is about the same level as the grid by columns, the sound power energy level can be shown in the following formula.

$$PWL = 10 + 10 \log S + 30 \log Z + 60 \log u \dots\dots(5)$$

If the square measurement of the cross-section is equal to 68 square meters and  $Z = 1.8$ , then the level of the self-generated noise generated by a splitter type sound suppressor during the peak flow volume is approximately 87 dB, which appears to be a proper level comparing the level at the outlet of the sound suppression device. The air (containing noise) that passed through the splitter type sound suppressor is further suppressed at a 90 degrees and a 180 degrees bent duct. The volume of the suppressed sound can not be clearly established due to the lack of data. It is estimated, however, that the calculation through the use of a 90 degrees bent duct alone results in 14 dB at 63 Hz and 18 dB at above 700 Hz. Therefore, the power level of the self-generated sound at the bent duct part at the maximum 63 Hz is estimated at 70 dB. (6) Accordingly, the self-generated sound at the

bent duct part has more than 10 dB difference compared to the outlet of the sound suppression device. The self-generated sound by the splitter type sound suppressor is also suppressed by the bent duct and becomes more than 10 dB difference compared to the sound power level at the outlet. Therefore, it is proper to set the square measurement of the flow passage cross-section at 68 square meters.

Fig. 6 Sound reduction by a variety of 90 degrees bent section

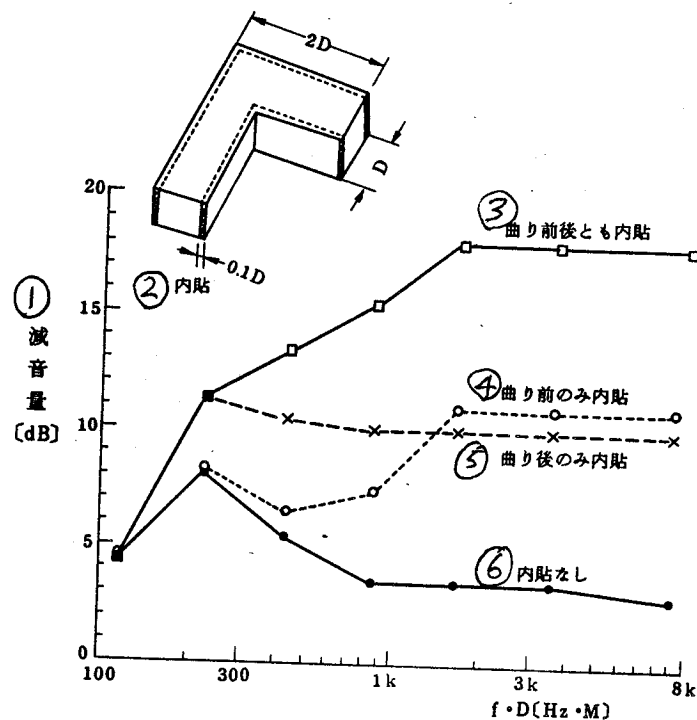


図6 各種直角曲りによる減音<sup>19)</sup>

1. volume of sound reduction 2. lining 3. lining at

before and after the bent part    4. lining before the bent  
part only    5. lining after the bent part only    6. no lining

[The necessary noise reduction level of a sound suppression device] is determined by the difference in the sound pressure level between the entrance of the sound suppression device and the outlet of the same. The sound pressure level of the outlet has already been explained. The sound pressure level of the entrance can not be determined unless the sound power energy discharged by the wind tunnel, the [room coefficient] of the location where the sound suppressor is located, the distance up to the entrance of the sound suppression device or revision of hearing are conducted. However, it is evident that the size of the room facing the entrance should be about 8 meters square judging from the square measurement of the cross-section of the flow passage. The condition of this room is as follows. The ceiling and the walls of this room should be made of 100 MM glass wool board, and the floor should be a concrete floor if the sound absorption by the surface of the room is to be determined so that the room coefficient for each frequency level can be set. From the above conditions, the sound pressure level at the entrance was estimated at 150 dB (O. A.). Therefore, the volume of sound suppression by the sound suppression device should be approximately 81 dB.

Fig. 7 The entire view of a sound suppressor (in construction at the factory)

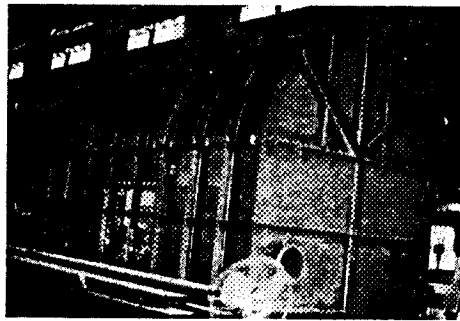


図7 サウンドサプレッサ  
全体図(工場内で製作中)

[Sound suppressors] The splitter type sound suppressors are capable of handling huge flow volume and are effective to handle wide range of sound. Therefore, this type is adopted for this device. An additional characteristic of this sound suppressor is that a sort of parallelism can be found between the size of this device and the characteristics of the sound suppression. It is said that larger the suppression device is, the more effective it is in suppressing the lower range of sound. (19) Based on this information, the sound suppression devices are arranged by size (from larger ones to smaller ones) from the upper stream to the lower stream. In addition to that, the shape of the sound suppression device is determined as the variable form splitter type sound suppressor so that the self-generated sound due to the flow resistance can also be suppressed. The size per one

step of this variable form splitter type sound suppressor is set at 2 M x 8 M so that installment work may be simplified. The oversized ones at the upper stream are structured so that they can be divided into two. The total length of the splitter type sound suppressor is set at about 20 M based upon the estimation of the sound suppression at 3 dB per 1 M. Since it is impossible to totally depend on this type of sound suppressor to totally finish the job due mainly to lack of sufficient data, 180 degrees and 90 degrees bent ducts are also used with the splitter type sound suppressors. As shown in Fig. 6, the bent duct devices are effective in handling high range of sound. Accordingly, it is most effective to use this type at the down stream where there is less transmitted sound from the walls. If we depend too much on the bent duct type device, then the whole device would become too large.

[Sound suppressor] The discharge tunnel located at the extreme down stream of the wind tunnel is far less in the square measurement of the flow passage of the sound suppressor devices. While large volume of air is discharged through this area, the sound suppressor device must be bent by 90 degrees of the axis of the wind tunnel due to the restriction of the construction site. Therefore, the flow at the entrance part of the sound suppressor was expected to become turbulent generating abnormal sound. In order to prevent the above situation from happening, the discharge tunnel was wrapped by



a semicircular cylinder made of steel (Fig. 7). Many holes (40 MM in diameter) were drilled at the part facing the entrance of the sound suppressor in order to jet-spray the air from the wind tunnel.

[Housing of the sound suppressor device] It is rather easy to decide the shape of the housing to contain the sound suppressors since the structure and the square measurement of the flow passage of the sound suppressors have already been determined. The sound pressure level within the housing becomes high at the upper stream and low at the lower stream. Therefore, there is not problem of self-generated sound at the upper stream even if the flow speed at the upper stream was high. In case the sound pressure level is high, the influence of the noise that is transmitted through the housing can not be ignored. Said transmission noise is almost impossible to eliminate as shown in the formula (6) and (7).

$$TLo \div 20 \log fM - 42.5 \dots\dots\dots(6)$$

$$TL \div TLo - 10 \log (0.23 TLo) \dots\dots(7)$$

The above formulas indicate the relationship that the transmission loss is increased by approximately 5 dB every time the thickness of the wall (surface density) is increased by two times. In other words, the above formulas clearly indicate that it is not practical to depend solely upon the thickness of the wall in order to gain high level of sound suppression. A double wall may be effectively used to remedy

the above problem. Yet, the real effect of the double wall is materialized only if it is possible to mechanically separate the two walls. The sound suppression walls in some instances generate a sort of resonance caused by an acoustic characteristic of the material used, and the transmission loss in some instances becomes smaller than what is shown in the formula (7). This point must not be overlooked in the design of the sound suppression walls. At the high sound range, lowering of the transmission loss is sometimes experienced by a sort of resonance between the sound pressure distribution on the surface of the wall by the sound waves which hit the wall in an angle and the original resonance distribution of the wall surface. This is called coincidence. The frequency of the coincidence is given by the formula (8).

$$f_c = C^2 / 1.8 Cbt \dots\dots(8)$$

The use of concrete in 20 CM to 30 CM thickness as the wall material of the housing results in the above described coincidence at 90 Hz to 60 Hz. Accordingly, the estimate of the transmission loss is obtained by the following formulas instead of the formula (7).

$$f \leq f_c; TL \div 18 \log f M - 44 \dots\dots\dots(9)$$

$$f > f_c; TL \div 0.7 TL_c + 20 \log \frac{f}{f_c} \dots\dots\dots(10)$$

Fig. 8 Influence of the background layer of air on sound absorption characteristics of porous material

1. sound absorption rate  
rate at a reverberation  
room

2. frequency

3. no background layer  
of air

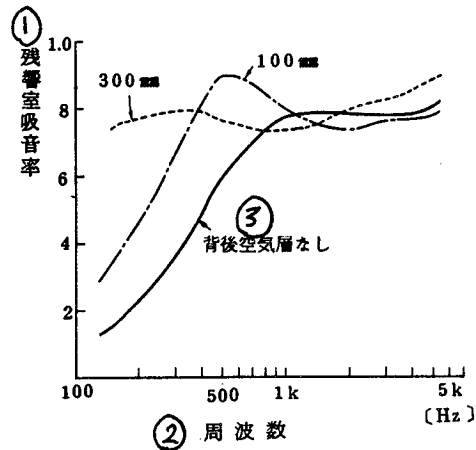


図8 多孔質材料の吸音特性に対する  
背後空気層の影響

The transmission loss of the double wall is shown by the following formula.

$$TL \div TL1 + 0.7 TL2 \dots\dots(11)$$

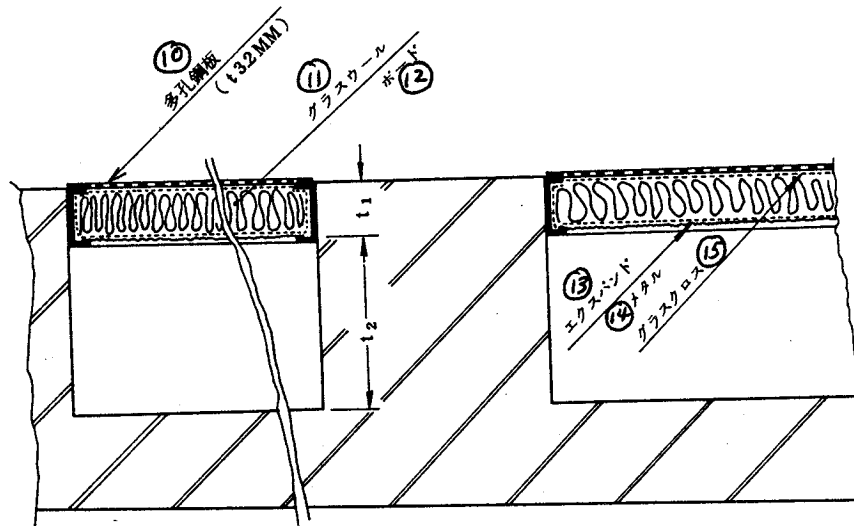
A double wall consisting of a 20 CM and a 30 CM concrete wall with 80 CM of space between the two results in 52 dB at 63 Hz according to the formulas (6) - (11).

The part where the transmission sound is the greatest is the ceiling (70 square meters) of the discharge tunnel. The sound pressure which is transmitted through the ceiling and which reaches the 100 M point is estimated as 35 dB at 63 Hz. In the case of a double wall, transmission phenomenon through the resonance of the air also takes place. This is called a low range sound resonance transmission, and its frequency is obtained through the following formula.

$$f_r \div \frac{1}{2\pi} \sqrt{\frac{M_1 + M_2}{M_1 M_2} \frac{\rho C^2}{d}} \dots\dots(12)$$

Fig. 9 Specification of the interior of the housing

① 場所	⑤ 放出筒室及び第1・2スプリッタ消音器室			⑥ 第3～6スプリッタ消音器室			⑦ 80°及び90°曲リダクト部		
	(MM) t <sub>1</sub>	(MM) t <sub>2</sub>	(kg/M <sup>3</sup> ) γ	(MM) t <sub>1</sub>	(MM) t <sub>2</sub>	(kg/M <sup>3</sup> ) γ	(MM) t <sub>1</sub>	(MM) t <sub>2</sub>	(kg/M <sup>3</sup> ) γ
②天井	100	0	64	150	550	48	150	450	48
③側壁面	100	0	64	150	400	48	150	400	48
④床面	⑧ コンクリートコテ仕上			⑧ コンクリートコテ仕上			⑨ アスファルト露出防水		



1. location 2. ceiling 3. wall surface 4. floor 5. discharge tube room, the first and the second splitter sound suppressor room 6. the third - the sixth splitter sound suppressor room 7. 180 degrees and 90 degrees bent duct part 8. concrete finished with a trowel 9. asphalt, exposed, water resistance 10. porous steel plate 11. glass wool 12. board 13. expand 14. metal 15. glass cloth

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In the case of the above described concrete double wall,  $f_r \div 4$  Hz. Therefore, its influence can be ignored.

From the above reason, square measurement of the flow passage is reduced at the upper stream in order to suppress the low range noise. The space created as the result of the reduction in the square measurement of the flow passage is utilized to install a double wall. In the case of steel reinforced concrete, the structure should take the outer wall structure form (columns or beams are placed inside the wall) so that a thick background air layer may be provided for the sound absorption walls using. (Fig. 8, 9, 10)

Fig. 10 Installment of the absorption wall with a layer of background air

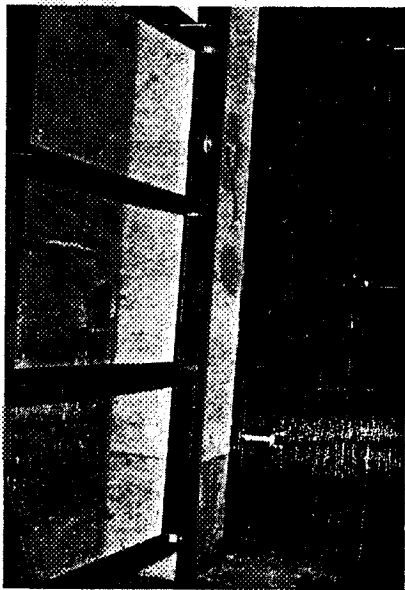


図10 背後空気層付吸音壁の取付状況

Fig. 11 Sound absorption wall (photo taken from the downstream side)

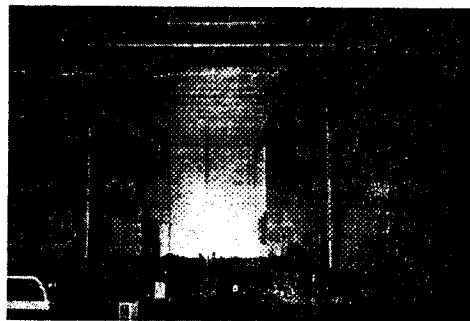


図11 吸音壁(変形スプリッタ型消音器取付前後流側から撮影)

## 5. DETAILED EXPLANATION OF THE STRUCTURE OF THE MUFFLER DEVICE

### 5.1 Variable form splitter type sound suppressor device

Based on the discussion of the previous chapter, the sound suppressor device is structured by six different steps of variable form splitter type sound suppressors as well as 90 degrees and 180 degrees bent ducts. The size of the first and the second variable form splitter type sound suppressor at the upper stream were determined at 0.9 M (width) x 5 M (length) x 7.5 M (height) so that noise suppression of lower range would be effectively accomplished. Since the flow speed is high in this area, the external shape of the device was made smooth in order to minimize the self-generated noise. In addition to that, glass wool boards were applied using glass cloth and a porous steel plate for the purpose of reducing the exfoliation of the sound suppression material. The density of the glass wool board was changed according to the flow speed. A noise blocking plates were inside the splitter in order to check the lowering of the sound absorption capability through the influence of the opposing surface. The details of the variable form splitters are shown in Fig. 12. There are seven first•second splitters, 13 third•fourth splitters, 21

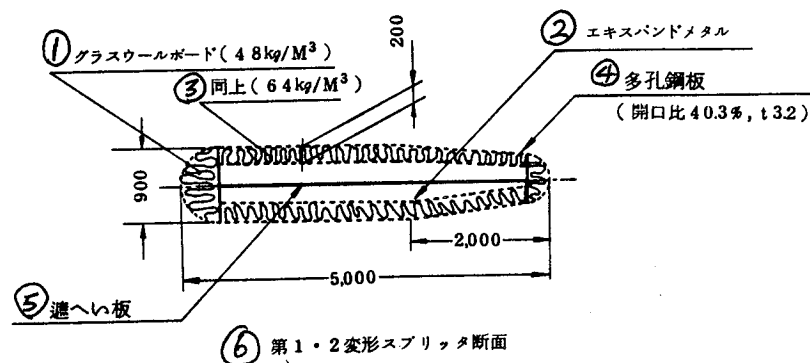
fifth•sixth splitters - a total of 41. The first and the second splitters among them are built in two sections since the total weight of each splitter is as high as 6 t. These two sections are welded together once installed as a part of the total device. Putting together all the device and parts was done by welding in order to minimize the risk of vibration during the operation.

## 5.2 Housing

A housing made of steel reinforced concrete (as shown in Fig. 3) was prepared to house a variety of sound suppression devices and more than 60 square meters of flow passages. The dimension of the housing was determined at 10 M x 40 M considering a variety of factors. In order to enable double wall structure at upstream area where the sound pressure level, a housing according to the wall structure (thickness of 30 CM) was established inside the housing between the sound suppressor room and the second splitter sound suppression device. In order to mechanically cut off the outer housing (20 CM in the wall thickness) from the inner housing, two separate structures were built including the base foundation. Utmost attention was paid to reduce the transmitted noise including the use of the expansion joints at the connection part. The square measurement of the flow passage of the first•second splitter sound suppressor part was increased from 46 square meters to 64 square meters so that

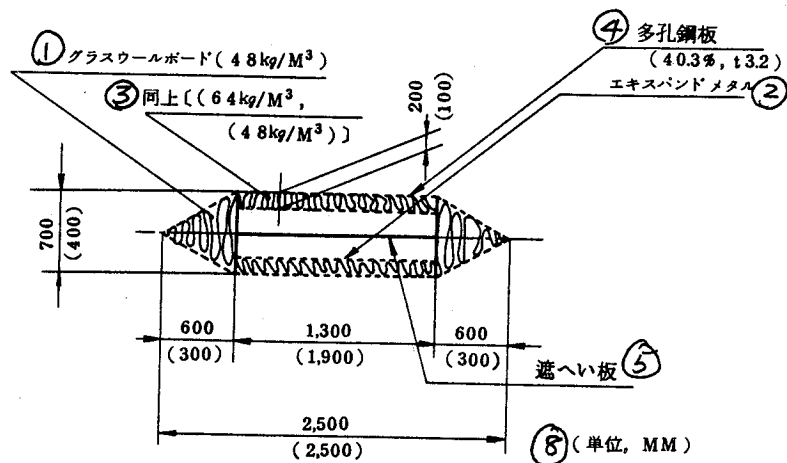
the air may be able to reduce speed freely. The ceiling and the walls of the inner housing was used as the sound absorption surface without the background air layer since no columns or beams are present (Fig. 9). The surface which contacts the air flow excluding the floor surface (concrete, water-resistant asphalt) from the outlet of the inner housing up to the entrance of the 90 degrees bent duct was completed using porous steel plates. Sound absorption boards made of glass cloth, glass wool boards, and expanded metal were prepared under the porous steel plates. Behind the steel plates, an air layer, 400 MM - 550 MM, was prepared. A steel mesh screen was placed at the entrance of the 90 degrees bent duct in order to block the entrance of birds. The downstream side of the steel mesh screen is surfaced by concrete in order to avoid the influence of rain water on the sound absorption material.

Fig. 12 Specification of the variable form splitter type sound suppressor





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⑦ 第 3・4 及び第 5・6 (( ) 内に示す) 変形スプリッター断面

⑨ 名 称	⑩ 数量 (基)	⑪ 基の重量 (トン)	⑫ 総重量 (トン)	⑬ 高さ (M) × 長さ (M) × 巾 (M)
⑭ 第 1・2 スプリッター消音器	7	6.0	42.0	7.5 × 5.0 × 0.9
⑮ 第 3・4	13	2.7	35.1	7.9 × 2.5 × 0.7
⑯ 第 5・6	21	2.3	48.3	7.9 × 2.5 × 0.3

図 12 変形スプリッター型消音器の仕様

1. glass wool board 2. expand metal 3. same as the above  
4. porous steel plate 5. blocking board 6. cross-section  
of the first・second variable splitters 7. cross-section of  
the 3rd・4th・5th・6th variable splitters 8. unit (MM) 9.  
name 10. number 11. weight of one device (ton) 12. total  
weight 13. height x length x width 14. 1st・2nd splitter  
sound suppression device 15. 3rd・4th splitter sound  
suppression device 16. 5th・6th splitter sound suppression  
device

The building behind the one story part is connected

with the sound suppression device with an opening, 1 M x 3 M. Located inside is a suction device (air filter, 19150 NM<sup>3</sup>/hour) of the air compressor system. It can be used for the purpose of suppressing the noise at the time of suction as well. It can also be used as a resonance room. Selection of the steel mesh screen was done considering the self-generated noise.

Fig. 13 Installation of the 1st variable form splitter type sound suppression device

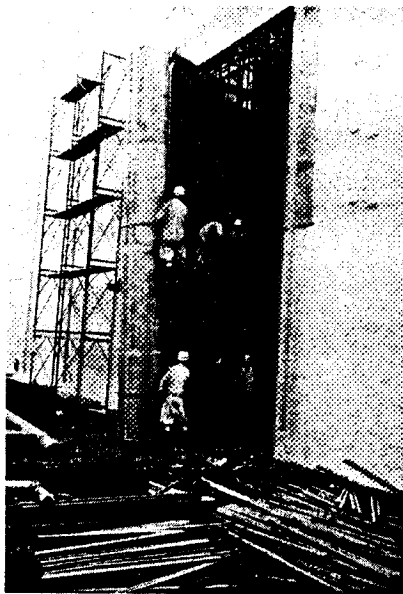


図13 第1変形スプリッター型消音器(前部)搬入状況

Fig. 14 Interior of the 1st·2nd variable form splitter type sound suppression device

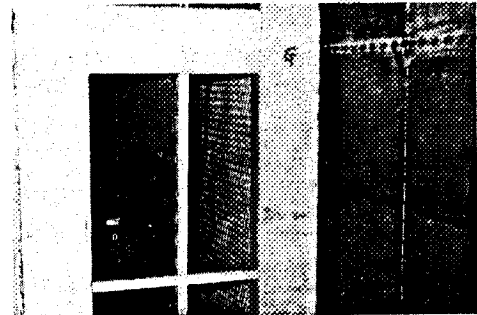


図14 第1・2変形スプリッター型消音器の内部

Fig. 15 Attachment of sound absorption material to the 3rd•4th variable splitter type sound suppression device

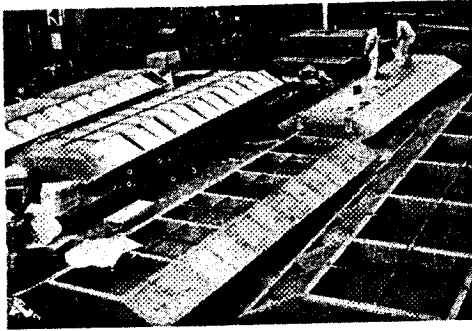


図15 第3・4変形スプリッター型消音器の吸音材組込作業

Fig. 16 The 6th variable form splitter type sound suppression device (photo taken from the downstream side)

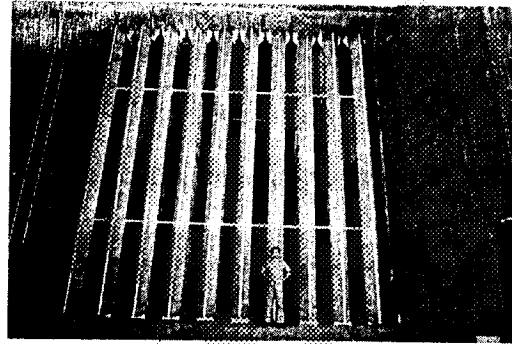


図16 第6変形スプリッター型消音器  
(下流側から撮影)

## 6. CHARACTERISTICS TEST

[General] Operational characteristics tests were conducted in order to examine if the performance characteristics of the finished sound suppression device were as good as its original design. The test was divided into two parts. The first test to measure the sound suppression performance of the variable splitter type sound suppression devices was done with a microphone attached to each step of the device. (Fig. 3) Sound that was generated by approximately 0.7 % of the maximum air flow was recorded using

a magnetic tape recorder and analyzed by each one octave band. As the result of the test, it was revealed that the maximum sound suppression of the six-step variable splitter type sound suppression device was 82 dB (at 500 Hz). It was also revealed that the noise generated from the second throat valve which was used as the sound source was almost flat in power spectrum density distribution.

The other test includes the measurement of the noise levels at the boundary of this research center as well as a variety of spots near the wind tunnel as the wind tunnel is operated at its maximum capacity. The result of the test revealed that it was impossible to measure the noise level at the boundary of this research center due to the high level of the non-pertinent noises in the vicinity of the check point. However, it was concluded that the device successfully achieved the designed level of the sound suppression based on the noise level gathered at the outlet of the sound suppression device.

#### 6.1 Sound suppression characteristics test of the variable form splitter type sound suppression device

Fig. 17 Characteristics of the variable form splitter type sound suppression device to be used with the exhaust silencer of the two-dimensional wind tunnel

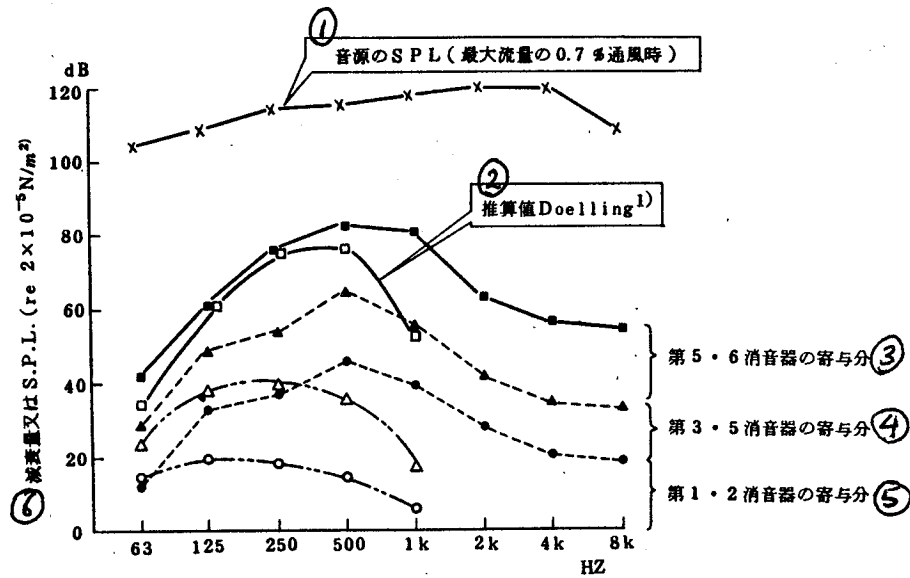


図17 二次元風洞消音装置用変形スプリッタ型消音器の特性

1. SPL of the sound source (at the time of 0.7 % of the maximum flow volume)
2. estimated figure
3. contribution by the 5th・6th sound suppressor
4. contribution by the 3rd・5th sound suppressor
5. contribution by the 1st・2nd sound suppressor
6. volume of the reduction or S. P. L.

[Test method] Self-generated noise of the second throat valve was used as the source of the noise for the test. Therefore, the second throat valve was put under a totally shut condition first. When the air pressure inside the wind tunnel reached 8 ata the second throat valve was opened about 0.8 % (of the fully opened condition). At the same time,

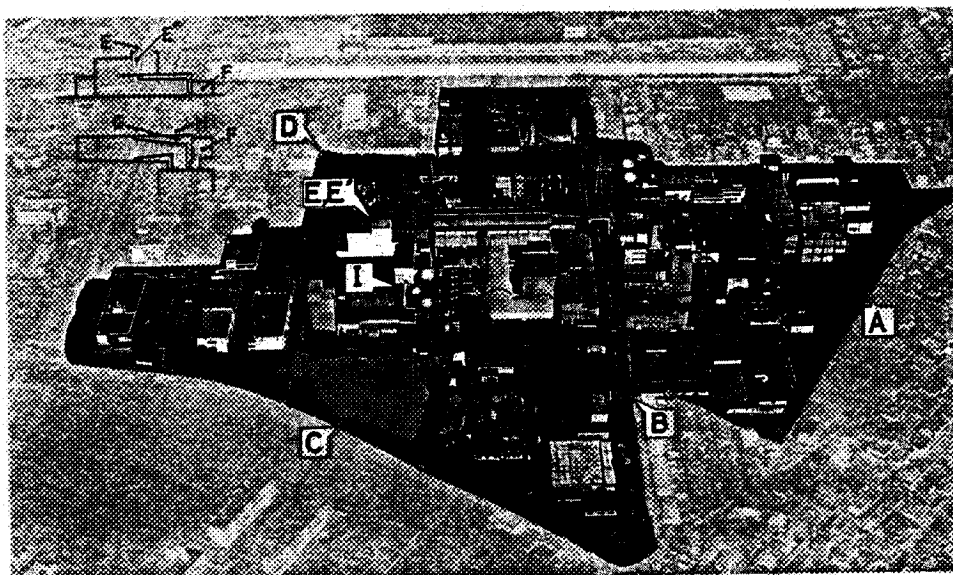
recording on magnetic tapes was made using eleven microphones set up at each critical point. The measurement points are as shown in Fig. 3. One microphone was set at the end of the discharge tunnel, and three microphones were set at the entrance of the first splitter type sound suppressor and at the exit of the sixth splitter type sound suppressor.

[Test result and discussion] The sound suppression characteristics of the splitter type sound suppressors can almost be concluded in  $f \cdot D$ , and a sort of parallelism is apparent between the frequency characteristics and the dimension of the device. The larger the size of the device is, the lower sound range the suppression characteristics move to. Therefore, both the 1st•2nd and the 5th•6th indicate the peak sound suppression at 500 Hz in spite of the fact that there are nearly three times difference in  $D$  between the two. (Fig. 17) Close observation of the measured figures indicates a clear peak at the 500 Hz by the 1st•2nd variable splitter type sound suppressors, while a rather flat characteristics are displayed by the 3rd•4th and the 5th•6th variable splitter type sound suppressors. If this volume of the suppressed sound is compared with the weight of each sound suppressor shown in Fig. 12, then the relationship between the production cost and the effectiveness of the finished product can be clearly seen. In other words, since the production cost of the splitter type sound suppressors is almost in proportion to

the weight thereof, the 1st•2nd splitter type sound suppressors possess superior sound suppression effect in low to high sound range in spite of the fact that its weight compared with other two types of sound suppressors is about the average. In addition to that, it has almost twice as much sound suppression power as the others at the mid range. Fig. 17 also includes an example of the estimated figures.

Although many methods to estimate the sound suppression volume have been made public in the past, it is important that all of these methods are corrected as needed to suit the need of the practical application according to the specific need of each situation. Therefore, collection of more data is vitally needed at this time. The sound power spectrum density distribution of the sound source is almost flat as shown in Fig. 17. This is the same sound as the one that is generated as the air, 8 ata, filled inside the wind tunnel is discharged to the atmosphere through the second throat valve. The result of the measurement corresponds the result of the similar devices obtained in foreign countries. The sound power level is almost the same as the estimated level.

Fig. 18 Location of the noise measurement



Tab. 1 Condition of air passage inside the wind tunnel

表 1 風胴の通風条件

Run No	① 集合胴圧力	② マッハ数	③ 流量	④ 第二スロート弁開度	⑤ 抽気弁開度
100	12 kg/cm <sup>2</sup> a	0.7	761 kg/秒	65%	0%
101	12 "	1.0	832	80 "	70 "
P	Run No 102のためのプリチャージ				
102	8 kg/cm <sup>2</sup> a	1.0	555	80 "	70 "
103	4 "	1.0	275	80 "	70 "

1. pressure level of the consolidation tunnel 2. mach number 3. flow volume 4. degree of the opening of the second throat valve 5. degree of the opening of the air injection valve 6. second

Tab. 2 Noise level at each location

表 2 各位置の騒音レベル総括表

Run No	① 位置 条件	A	B	C	D	E	E'	F	G	H	I
100	暗騒音③	49~64	58~60	64~76	60	65	—	<72	—	67	—
	通風時④	49~64	58~60	78	68	81	—	82	—	78	—
101	暗騒音③	48~54	—	60~73	55	62	—	<76	<85	60~65	<103
	通風時④	51	—	76	70	78	—	86	95	78	113



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P #102の ブリーチャー②	暗騒音③	—	—	63~78	—	—	59	<49	—	69	< 96
	通風時④	—	—	77	—	—	71	59	—	76	106
102	暗騒音③	42~48	—	62~75	58	—	60	<63	<80	70	< 98
	通風時④	49	—	72	62	—	73	73	90	75	108
103	暗騒音③	45~51	65	65~72	58	—	60	<58	<76	68	< 77
	通風時④	45~51	66	65~72	58	—	32	68	86	69	87

⑤ 単位; dB(A)

1. location/ condition    2. pre-charge    3. non-pertinent  
noise    4. during the period of air passage    5. unit

## 6.2 General performance test

[Test method] Operation of the wind tunnel must be identical to the actual operation. The noise generated during the operation identical to the actual operation was measured at nine locations including four locations at the boundary of this research center. (Fig. 18) All measurement was taken simultaneously. In order to assume the simultaneity, a net of transceivers was widely used among the measurement locations. The operating condition of the wind tunnel was as shown in Tab. 1. The operating condition obtained through calculation to generate the maximum level of noise could not be included since the most frequency used operation as well as the operation which generates the most flow volume were considered more important. "P" indicates the condition in which the second throat valve is fully opened and the wind tunnel is completely filled with air.

[Test result and discussion] As clearly shown in Tab. 2, the highest level of noise was recorded at the location I. The noise recorded at the location I is thought to have been generated by the air storage tank and the air pipe connected to it. The counter measure is thought to be rather difficult because of the financial and legal restriction including the pressurized gas storage ordinance, but no major problem has been experienced during the past ten years of the continuous operation.

The noise level at E point and E' point (outlet part) in the Run No. 100 and 101 were measured by placing a microphone at 500 MM above the outlet. (This location was designated as the E point.) After the Run No. P, the position of the microphone was lowered to 2500 MM (inside the outlet) (This location was designated as the E' point.) It is believed that the noise level at the E' point during the Run No. P must have been from the source other than the outlet itself since hardly no air flow was present at that time. The highest noise level among them was that of the I point as shown in Tab. 2. It is assumed that the data collected at the position E' during the Run No. P must have been heavily influenced by this figure. In this case, weakening of the noise level by 35 dB is seen between the I point and the E' point. If these data are applied to the Run No. 101, the result of the E point can be obtained by  $113 - 35 = 78$  dB (A),

which agrees with the calculated figure at the ie of operation. Therefore, the noise level of the E point in reference to the Run No. 101 without considering the influence from the I point must be below  $78 - 10 = 68$  dB (A). Therefore, it is believed that the sound suppression device that we have completed possesses the designed performance characteristics. Th influence of the noise from the point I can also be estimated through the noise spectrum analysis. Fig. 19 and Fig. 20 show the noise spectrum of the G point which is considered to be the least influenced by the I point, the F point (indoor) which is considered to be fairly influenced by the I point and the E, E' and H points which are considered to be the most influenced by the I point. At the I point (Fig. 21), the peak is clearly be seen around 1 KHz, while no such peak is visible at the G point (Fig. 19). Therefore, the influence of the point I over the points E and E' is thought to be quite strong from these facts as well. Incidentally, the example in which the peak frequency of the self-generated noise of the pipe works is seen in the vicinity of 1 KHz has been reported in the examples of other wind tunnels. (11)

Fig. 19 Noise spectrum of various test points

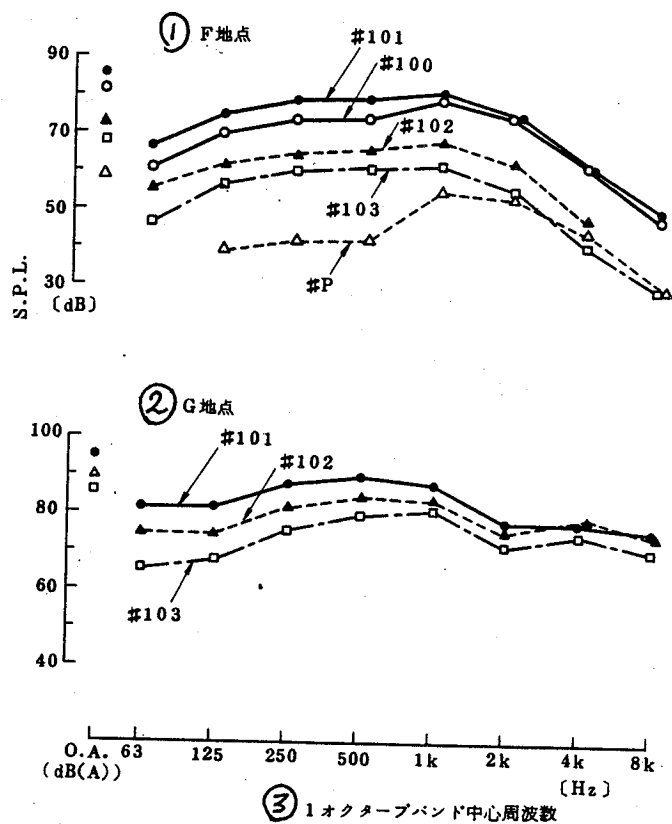


図 19 計測地点の騒音スペクトル

1. F point 2. G point 3. 1 octave band center frequency

[Noise condition at the boundary of the research center] The A point which is the farthest point from the outlet among four measurement points is approximately 290 M from the outlet of the sound suppression device. (Fig. 18) Between the two locations are several buildings which could act as the sound blocking devices. In addition to that, to

the rear is a public road which is usually busy with vehicular traffic. Occasionally, light airplanes fly by the research center. This is why non-pertinent noise is quite heavy at the boundary of the research center. Therefore, absolutely no noise of the wind tunnel could be heard during the Run No. 100 and 103. Only a low level noise (of the wind tunnel) could be heard during the Run No. 101 and 102.

The point B which is far apart from the public road is the least influenced by the vehicular traffic, yet the noise level by the airplanes and the like was extremely high making putting this location under the same category as the point A.

The point C was greatly influenced by busy vehicular traffic since it is sided by a broad public road. It was extremely difficult to measure the noise level of the wind tunnel here.

The D point which is the closest from the outlet (approximately 100 M) and far apart from the public roads was found to be the location with the least difficulty to measure the noise level from the outlet of the sound suppression device. Yet, the influence of the I point had to be considered.

Fig. 20 Noise spectrum at each measurement point

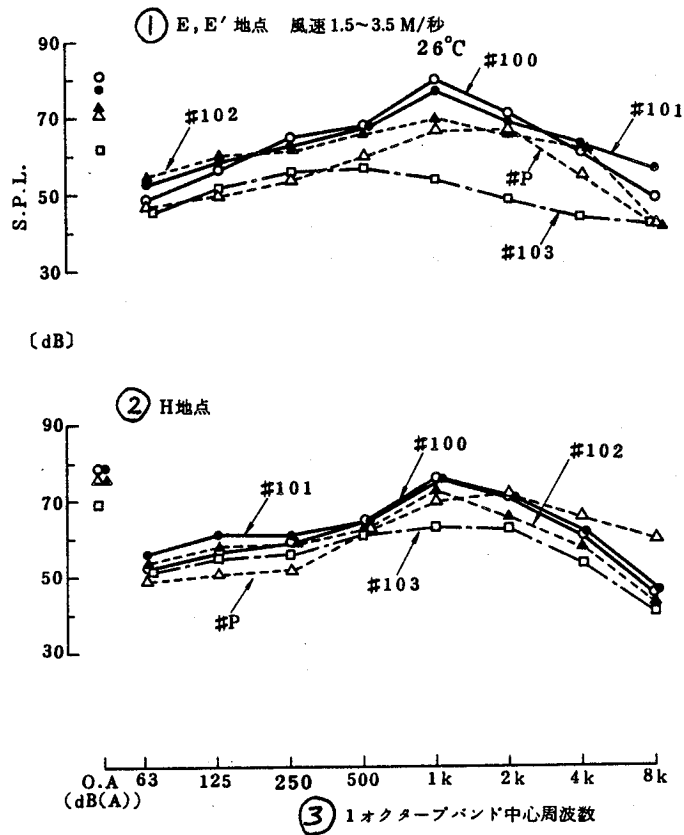


図 20 計測地点の騒音スペクトル

1. E, E' point; wind speed, 1.5 - 3.5 M/sec 2. H point 3.  
one octave band center frequency

Fig. 21 Noise spectrum at each measurement point

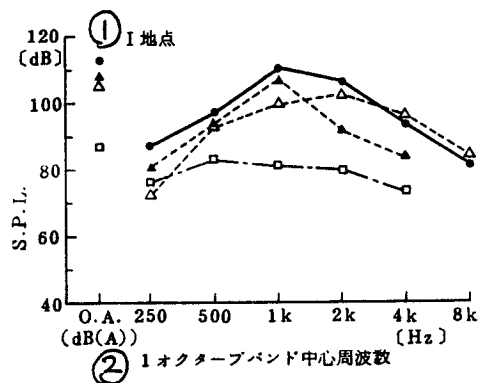


図 21 計測地点の騒音スペクトル

1. I point    2. 1 octave band center frequency

## 7. CONCLUSION

The following points have been clarified through the design, production and test process of the exhaust silencer for blow type high pressure two-dimensional wind tunnel.

(i) In case variable form splitter type sound suppressors are combined in several steps, the noise reduction characteristics according to the rules of the parallelism signified by  $f \cdot D$  can not necessarily be gained.

(ii) The maximum noise suppression that can be achieved using variable form splitter type sound suppressors, 6 steps x 20 M in total length x 8 M in height x 9 M in width, is 82 dB (500 Hz).

(iii) In the case of the blow type wind tunnel, the noise generated from the air storage tank as well as its air tube system can not be ignored. The two-dimensional wind tunnel has achieved 300 separate cases of actual operation since its completion during which time absolutely no operational problems have been experienced in spite of the severe conditions imposed on the device. Therefore, it is believed that the initial objective of this project has been fully accomplished.

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16. Abstract This paper presents a description of the design construction and performance of the exhaust silencer for the NAL high Reynolds number two-dimensional transonic blow down wind tunnel, which was completed in October 1979. The silencer is a two-storied construction made of reinforced concrete, 40 <sup>M</sup> long, 10 <sup>M</sup> wide and 19 <sup>M</sup> high and entirely enclosed by thick concrete walls. The upstream part of the first story, particularly, is covered with double walls, the thickness of the two walls being 0.3 <sup>M</sup> (inner wall) and 0.2 <sup>M</sup> (outer wall), respectively. A noise reduction system using three kinds of parallel baffles and two kinds of lined bends is adopted for the wind tunnel exhaust noise.			
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